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# A CONCEPT FOR ASSISTING REMOTE IR DAMAGE ASSESSMENT BY COUPLING NUMERICAL FIRE SUPPRESSION MODELS WITH THERMAL SIGNATURE MODELS

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## ABSTRACT

Program Managers (PMs) under the Program Executive Office for Ground Combat Systems (PEO-GCS), funded the U.S. Army CECOM RD&E Center (CERDEC) to develop and apply a 3D numerical model to predict the performance of automatic fire suppression systems in armored combat vehicles with Halon and Halon alternative fire suppressants. Running the model without suppression allows predictions of fuel spray fire propagation in defeated vehicles and the resulting internal temperatures. The model also predicts the extinction of the fire due to oxygen availability. Hence, transient heat flux to interior surfaces can be predicted until fire extinction and can subsequently used as boundary conditions for a thermal signature code such as PRIZM or MUSES.

A numerical fireball model specially formulated for fire suppression is incorporated into a 3D, transient, hybrid, finite-volume, finite element code with transient tracking of JP8 and fire suppressant particles. The numerical fireball model consists of a flame front submodel driven by finite-rate kinetics that describe the reactions between sprayed JP8 fuel particles, oxygen and suppressant particles. The purpose of the numerical fireball model is to predict fires resulting from fuel tank or pressurized fuel line penetrations.

This information is reported in order to propose the use of the PEO-GCS Fire Suppression Model as input to thermal signature prediction models. The proposed result of this concept would be to gain the ability to predict thermal signatures of defeated enemy armored vehicles for comparison with thermal images from remote IR sensors for damage assessment purposes. This concept would be most valuable when major exterior structural damage (turret separation, etc.) is not present as evidence for damage assessment purposes.

## INTRODUCTION

Damage assessment of armored vehicles is often challenging when there is a lack of exterior clues such as turret separation or large soot coverage. Hence, this paper proposes a concept to assist those involved in damage assessment of armored vehicles where few exterior clues exist. The concept uses time lagged evidence of a large internal heat release due to catastrophic fires in armored vehicles. The resulting time-temperature history of vehicle armor is lagging in time due to the heat capacity of armor. For damage assessment purposes, the advantage of high heat capacity in metallic armor is that it can store large amounts of heat which are then released slowly to the atmosphere and hence can be sensed by infrared sensors for relatively long periods of time

## METHODS

*Time Lagged Armor Heat Release*

Thermal analyses involving unclassified work on armored vehicles often use the assumption that the thermal properties of special recipe armor can be approximated by the thermal properties of lead. Additionally, the lumped heat capacity technique can be used in transient thermal predictions where the surface convection resistance is very large compared with the internal conduction resistance. A criterion to test this assumption is the parameter from Chapman (1974),

$$hm/(\rho Ak) < 0.1 \qquad 1)$$

where: h = convective heat transfer coefficient,
m = vehicle mass,
ρ = armor density,
A = exterior surface area of armor, and
k = thermal conductivity of armor.

The value of this criterion is approximately 0.005 and 0.004 for lead-like and aluminum-like armor recipes. Hence, this assumption was used to derive the following first order, linear, ordinary differential equation which expresses, in general form, the armor temperature resulting from an interior fire:

$$dT/dt + ZT = K \qquad 2)$$

where: T = armor temperature,
t = time,
$Z1 = (1/c_p m)*(h_i A_i + h_\infty A_\infty)$,
$K = (h_i A_i/(c_p m))T_i + (h_\infty A_\infty/(c_p m))T_\infty$,
Ti = combustion gas temperature adjacent to interior walls
T∞ = outside air temperature
$c_p$ = heat capacity of armor,
$A_i$ = interior surface area, and
$A_\infty$ = outside surface area.

The solution of equation 2 was found using the method of separation, which yielded the following expression for the armor time-temperature history, during the fire:

$$T = (T_o - K/Z)e^{-Z1t} + K/Z \qquad 3)$$

where: $T_o$ = initial temperature of armor

Equation 4 below from Holman (1976), mathematically describes the armor cooling period after the fire is extinct,

$$T = (T_o - T_\infty)e^{-Z2t} + T_\infty \qquad 4)$$

where: $Z2 = (h_\infty A_\infty)/(c_p m)$.

Resulting predictions are for the conditions of, 1) 300 seconds of heat from fires inside of 20 ton and 40 ton armored vehicles, in the Army Hot Dry (Desert) condition of 49C (120F), 2) a 10 mph wind, 3) desert sand background temperature of (60 C)140F, and 4) an initial armor temperature equal to the desert sand background temperature. This study reports predictions that are bounded by the assumption that the fire will heat the gases adjacent to the interior walls to temperatures between the lower and upper bounds of 400 C (750F) (673K) and 1000 C (1830 F) (1273 K) respectively, with a mid-bound of 700 C (1292 F) (973 K). The combustion gas and fire temperature bounds were chosen to agree with measurements conducted by the Army's Aberdeen Test Center and reported in Gritzo et al. (1999). These predictions also

assume that the fire intensity remains constant throughout the 300 second (5 minute) fire exposure period. Predictions for shorter fire exposure times can be extrapolated from Figures 1, 2 and 3.
This study used an example from Driggers et al. (1999) of a Second Generation Forward-Looking Infrared (FLIR) imager and a standard 2.3 x 2.3 m NATO target with a 1.25 C target-background temperature difference. The conditions were 1) clear. 2) the standard U.S. atmosphere and 3) an altitude of 0.5 km above sea level. Values for the 50% number of cycles across target $N_{50}$ for identification, recognition and detection were 0.75, 3.0 and 6.0. respectively. For this example, Driggers et al. (1999) predicted that the probability of detection is greater than 0.9 for distances up to 5 km (3.1 miles). Much greater detection distances are expected for the relatively large target-background temperature differences considered in this study.

Combining the prediction by Driggers et al. (1999) with the predictions from Equations 3 and 4 above, a 20 ton target with a 1.25 C target-background temperature difference is detectable up to 1.0, 1.5 and 1.8 hrs, for interior combustion gases of 400, 700 and 1000 C, respectively, for a 300 second (5 min) fire (Figures 1, 2 and 3). A 40 ton target with a 1.25 C target-background temperature difference is detectable up to 1.4, 2.1 and 2.5 hrs, for interior combustion gases of 400, 700 and 1000C, respectively, for a 300 second (5 min) fire (Figures 1, 2 and 3).

Driggers et al. (1999) reported that typical, ground target, target-background temperature differences were in the range from 1.25 to 4 C. Therefore, thermal signatures resulting from internal fires can only be distinguished for target-background temperature differences greater than 4 C. For a 20 ton target, the target-background temperature difference is greater than 4 C for up to 0.9, 1.3 and 1.6 hrs. for interior combustion gases of 400, 700 and 1000C, respectively, for a 300 second (5 min) fire (Figures 1, 2 and 3). Likewise, for a 40 ton target, the target-background temperature difference is greater than 4 C for up to 1.0, 1.7 and 2.2 hrs, for interior combustion gases of 400, 700 and 1000C, respectively, for a 300 second (5 min) fire (Figures 1, 2 and 3). Hence, it seems plausible that the time periods over which defeated vehicles have a target-background temperature difference over 4 C are long enough to provide an interior fire signature for assessment and comparison with predicted signatures.

Figures 1, 2 and 3 also show that, in the event of such catastrophic fires as are considered in this study, light armored vehicles are predicted to have greater target-background temperature differences than more heavily armored vehicles. Damage assessment IR surveillance equipment can therefore detect these signatures from light armored vehicles with greater probability and at greater distances than from heavily armored vehicles. However, the window of opportunity to detect these thermal signatures from light armored vehicles is shorter than for heavily armored vehicles (Figures 1, 2 and 3), making timely damage assessment more crucial in these cases.

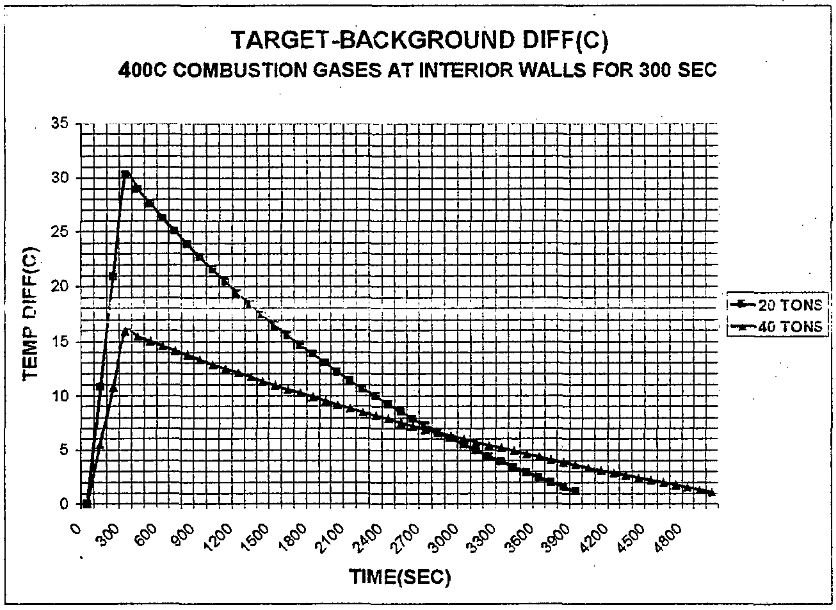


Figure 1. Target-Background Temperature Difference for lower bound of fire intensity exposing 400 C (750F)(673K) hot gases in the interior walls of a 20 ton and a 40 ton armored vehicle for a 300 second fire exposure time.

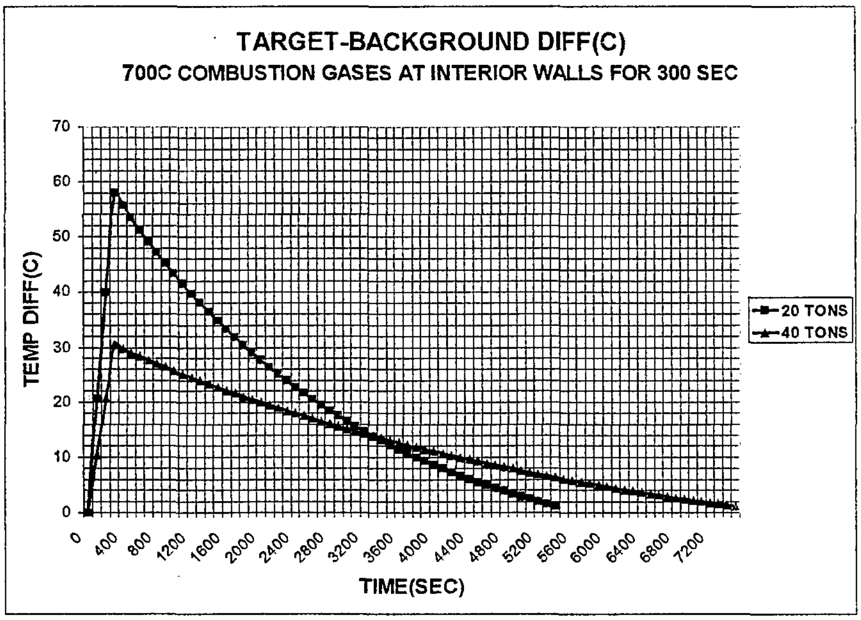


Figure 2. Target-Background Temperature Difference for lower bound of fire intensity exposing 700 C (1292 F)(973 K) hot gases in the interior walls of a 20 ton and a 40 ton armored vehicle for a 300 second fire exposure time.

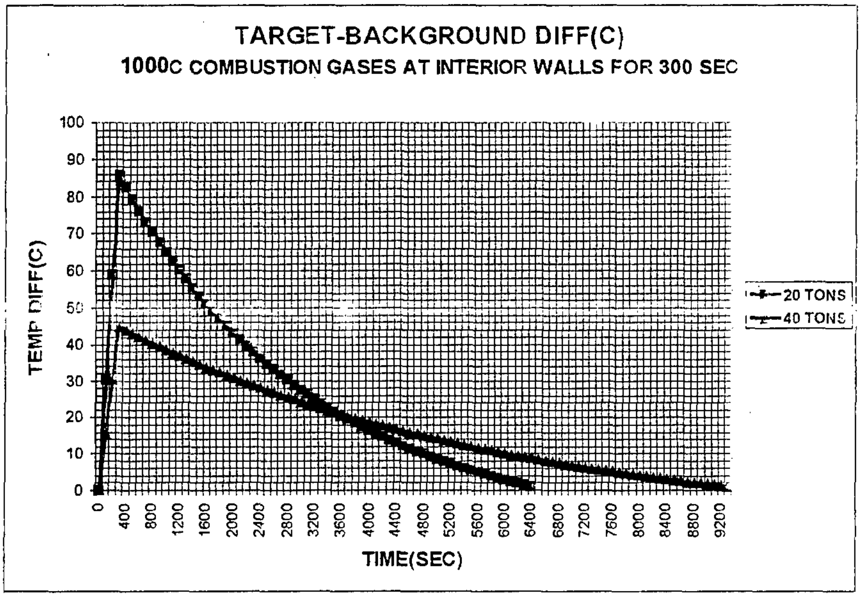


Figure 3. Target-Background Temperature Difference for lower bound of fire intensity exposing 1000 C (1830 F) (1273 K) hot gases in the interior walls of a 20 ton and a 40 ton armored vehicle for a 300 second fire exposure time.

Program Managers (PMs) under the Program Executive Office for Ground Combat Systems (PEO-GCS), funded the U.S. Army CECOM RD&E Center (CERDEC) to develop and apply a 3D numerical model to predict the performance of automatic fire suppression systems in armored combat vehicles with Halon and Halon alternative fire suppressants (Blackwell et al. 2000, Blackwell et al. 2001a, Blackwell et. al. 2001b, Blackwell et al. 2002a, Blackwell et al. 2002b, Skaggs et al. 2002). Running the model without suppression allows predictions of fire propagation in defeated vehicles and the resulting internal temperatures. The model also predicts the extinction of the fire due to oxygen availability. Hence, transient heat flux to interior surfaces can be predicted until fire extinction and subsequently used as boundary conditions for a thermal signature code.

This information is reported in order to propose the use of the PEO-GCS Fire Suppression Model as input to thermal signature prediction models. The proposed result of this concept would be predicted thermal signatures of defeated enemy armored vehicles for comparison with thermal images from remote thermal sensors for damage assessment. This concept would be most valuable when major structural damage (turret separation, etc.) is not present for damage assessment purposes.

*Numerical Code Description*

A numerical, conservative, hybrid finite volume-finite element formulation was used to solve the steady state equations for mass, momentum, energy and the transport equations for turbulent kinetic energy and the dissipation of turbulent kinetic energy. The commercial code is licensed by AEA Technology under the name of CFXTASCflow and has multi-block, body-fitted coordinate and local grid refinement capability.

The differencing scheme used for the advective terms was the mass-weighted scheme in conjunction with Physical Advection Correction which is formerly 2$^{nd}$ order accurate (Huget, 1985; Raithby, 1976; Lillington, 1981; Raw, 1985). The 2$^{nd}$ order, Central Differencing scheme was used for the diffusion terms. For continuity, pressure velocity correction was solved in a coupled manner and a modified Rhie Chow Interpolation was used to smooth out numerical oscillations in the solution and yield an error on the order of the 4$^{th}$ derivative.

Transient spray particles of fuel were modeled in the Lagrangian frame of reference and the gas species and reactions were modeled in the Eulerian frame of reference. The fire is computationally ignited with a small volumetric heat source of 20 to 30 kW near the ballistically created hole from which fuel spray is injected into the domain.

Most of the commercial code is parallel for shared memory machines and distributed machines. The relevant submodels for fire predictions that are not parallel are the submodels for, 1) transient particle tracking of fuel particles, and 2) fire. Future plans include the parallelization of these capabilities for PC clusters and for shared memory machines which are common in DoD High Performance Computing Centers.

*Suppression/Combustion Submodel Description*

The commercial, numerical code was customized to predict fire propagation resulting from a ballistic threat through a fuel tank or pressurized fuel line. Code enhancements relevant to the concept discussed herein include, 1) JP8 spray fires using the Eddy Dissipation Concept (EDC) submodel, with modifications by Rasmussen and Myken (1994), in conjunction with the flame front submodel with flame speed modifications derived from data by Linteris and Truett (1995) and 2) a two reaction mechanism for JP8 combustion by Westbrook and Dyer (1981)(Blackwell et al. 2000). The flame front submodel is driven by finite-rate kinetics that describes the reactions between sprayed JP8 fuel particles, oxygen and suppressant particles. Turbulence was modeled using the two equation k-e model (Launder and Spalding, 1972 and 1974). Radiation was modeled using the Gibbs model, which is applicable to opaque domains. A discrete ordinance radiation model was available but was judged to be too computationally expensive in comparison to the Gibbs model, which is acceptable for opaque domains, such as has been observed in recent ballistic tests by Skaggs (2003). Recent high speed video of ballistic tests by Skaggs (2003) compared with high speed video of spray generator initiated fires by ATC (1999), show the domain is much more opaque in the ballistic event. The author postulates that the increased opacity resulting from the ballistic event is due to 1) soot, 2) spall, 3) behind armor debris and 4) other ballistically airborne particles. Soot was modeled using the Magnussen soot model. Fuel spray boundary conditions for the PEO-GCS Fire Suppression Model are predicted using the Fire Prediction Model developed by Andy Pascal of Enthalpy, Inc. for the Air Force or by using spray generator data that was measured and reported in Reed et. al. (2002).

## DISCUSSION

Program Managers (PMs) under the Program Executive Office for Ground Combat Systems (PEO-GCS), funded the U.S. Army CECOM RD&E Center (CERDEC) to develop and apply a 3D numerical model to predict the performance of automatic fire suppression systems in armored combat vehicles with Halon and Halon alternative fire suppressants. Running the model without suppression allows predictions of fuel spray fire propagation in defeated vehicles and the resulting internal temperatures. The model also predicts the extinction of the fire due to oxygen availability. Hence, transient temperatures of combustion gases adjacent to interior surfaces can be predicted until fire extinction and can subsequently used as boundary conditions for a thermal signature code such as PRIZM or MUSES. Figure 4 shows an example of output from the PEO-GCS Fire Suppression Model, where hot gas temperatures adjacent to crew faces are predicted versus time. Time-temperature histories at the interior walls could be stored and input as boundary conditions in a numerical thermal signature code like PRIZM or MUSES. The proposed result of this concept would be gain the ability to predict thermal signatures of defeated enemy armored vehicles for comparison with thermal images from remote IR sensors for damage assessment purposes. This concept would be most valuable when major exterior structural damage (turret separation, etc.) is not present as evidence for damage assessment purposes.

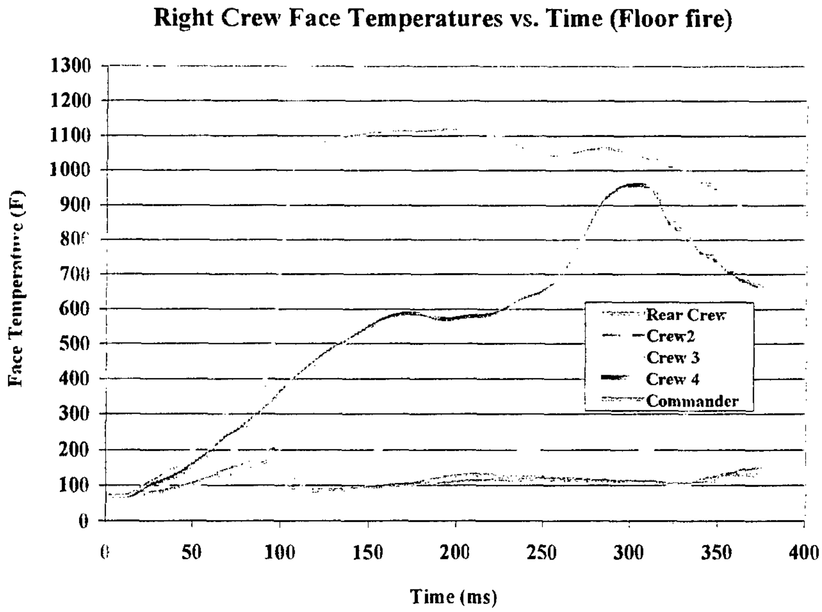


Figure 4. Predicted Crew Facial Temperatures versus time (Blackwell et. al., 2002b).

## CONCLUSIONS

The existing PEO-GCS Fire Suppression Model could provide transient, thermal boundary conditions to numerical thermal signature models of enemy armored vehicles for the purpose of predicting the thermal signature associated with an internal catastrophic fire, hence, indicating a kill. This concept would be most valuable when major exterior structural damage (turret separation, etc.) is not present for visual damage assessment.


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